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Feature-based attentional interference revealed in perceptual errors and lags

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ABSTRACT

According to a limited-resource account of feature-based attention, dividing feature-based attention by selecting targets on the basis of different features dilutes its power. Multiple-feature costs have been documented previously, but it is not clear whether the multiple-feature cost arose at the selection (segregating targets from non-targets) stage predicted by the limited-resource account. The cost might instead result from a post-selection difficulty in processing or accessing the contents of the targets. By defining the targets with a selection attribute (color) that is very distinct from the attribute participants must access and report (spatial period), we were able to manipulate the selection process independently from the access stage. We still found a cost for different selection features (colors), suggesting that multiple-feature costs can arise at the selection stage. The cost was only significant however when distracters were present that shared the selection features. The cost manifested not only as greater errors or less precision in reporting the access attribute (spatial period), but also as an increased temporal lag between the physical stimuli and the reported percept. In summary, splitting selection among different features incurred little or no penalty by itself, but selection interference by distracters sharing target features could be large and could slow processing.

1. Introduction

1.1. Feature-based attention

Attention can facilitate processing via selection of locations in the visual field (Eriksen & Yeh, 1985; Posner, Snyder, & Davidson, 1980). In addition to this spatial process, attentional enhancement may also work via features besides locations. When an observer attends to a specific feature such as the color red, the processing of other red stimuli can be enhanced, even if they are irrelevant to the task. This processing enhancement via attending to features is referred to as *feature-based attention* (see Carrasco (2011) for a review). In the current study, the term *feature* refers to a specific feature value (e.g., the color of red) whereas the term *attribute* refers to the whole dimension (e.g., color).

Evidence for feature-based attention has been found in the responses of neurons in V4 (Bichot, Rossi, & Desimone, 2005; David et al., 2008; McAdams & Maunsell, 2000; Motter, 1994a, 1994b), MT (Buracas & Boynton, 2007; Martinez-Trujillo & Treue, 2004; Treue & Martinez-Trujillo, 1999), IT (Chelazzi et al., 1993), and frontal eye fields (Bichot & Schall, 1999). In Martinez-Trujillo and Treue's (2004) study, for example, macaque monkeys were trained to attend to a stimulus, and neural responses to a second, irrelevant stimulus differed depending on which feature the monkey was attending to in the first stimulus. Feature-based attention was also documented in the human brain by fMRI (Kamitani & Tong, 2005; McMains et al., 2007; Saenz, Buracas, & Boynton, 2002; Serences & Boynton, 2007). In Saenz, Buracas, and Boynton's (2002) study, for example, they found that areas V1, V2, V3, and MT+ respond more strongly to an ignored stimulus when it shares a feature with the target. Furthermore, an ERP study in humans demonstrated that the P1 component elicited by an unattended stimulus was modulated by the color attended in the opposite target visual field as early as 100 ms after stimulus onset (Zhang & Luck, 2009).

Behavioral evidence for feature-based attention has also been found (Kanai, Tsuchiya, & Verstraten, 2006; Lankheet & Verstraten, 1995; Liu, Larsson, & Carrasco, 2007; Rossi & Paradiso, 1995; White & Carrasco, 2011; Zirnsak & Hamker, 2010). In Rossi and Paradiso's (1995) study, for example, the primary task was to discriminate the orientation of two consecutively presented Gabor patches at the foveal location. The secondary task was to detect a near-threshold grating in the periphery, which was the only other stimulus presented. They found that perceptual sensitivity to the peripheral stimulus was enhanced if it had a similar orientation to the foveal primary targets. This suggests that when the observer attends to a particular feature, all stimuli possessing this feature can influence the response no matter where they are in the visual field.

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Attention is often conceived of as a finite resource. When there are more targets to attend to, the resource is spread more thinly and attention has less effect on each target. The validity of this is frequently investigated in experiments requiring people to attend to different numbers of objects or different numbers of locations.

Feature-based attention might also reflect a finite resource that can be parceled out among multiple feature values. If so, then attending to two features should result in poorer performance than attending to one feature, even when the number of target objects and locations is the same.

Splitting attention between two features does indeed appear to have a cost (Lu & Itti, 2005; Saenz, Buracas, & Boynton, 2003; Sally, Vidnyansky, & Papathomas, 2009). For the task in each of these studies, we will refer to the *selection* attribute, which defines the attribute the participant uses to segregate target from non-target stimuli, and the *access* attribute, which is the aspect of the targets the participant must report (cf. Huang & Pashler, 2007).

In Saenz, Buracas, and Boynton's (2003) study, a pair of dot fields was presented on both the left side of fixation and the right side of fixation. Each pair comprised one field of dots moving upward superimposed with another field of dots moving downward. Participants were required to monitor one set of dots on each side, defined by the *selection* attribute of motion direction, which is the attribute to segregate the target from superimposed non-targets. In the dissimilar-feature condition, the participant might be asked to monitor the dots on the left that moved upward and the dots on the right moving downward. In the same-feature conditions they would monitor either the dots moving upward on both sides or those moving downward on both sides. The task was to detect whether either of the targets changed speed. In our terminology, the *access* attribute was speed, while the *selection* attribute was direction. The result of the experiments was that performance of the speed change detection was better when the motion direction to be selected was the same on both sides rather than different. We call this a multiple-feature cost. A cost was also observed in another experiment of Saenz, Buracas, and Boynton (2003), where detection of a luminance change was harder when the two sets of dots differed in color.

1.2. Selection vs. access

Does the multiple-feature cost arise at the stage of *selection* or *access*, or both? The answer is not clear from previous studies. In the case of the speed discrimination task in Saenz, Buracas, and Boynton's (2003) study, the multiple-feature cost might be due to a difficulty of *selection*, meaning that segregating the targets from non-targets is harder when the two targets move in different directions. In the case of their luminance discrimination task, a selection difficulty would mean that segregating targets from non-targets is harder when the targets have different colors. This seems to be the usual interpretation of findings in feature-based attention studies, although the distinction between selection and access may not be explicit.

The multiple-feature cost might alternatively occur after target selection, in processing the aspect of the target relevant to the task – we refer to this as *access*. A multiple-feature cost for access only, not selection, might conceivably account for the findings of Saenz, Buracas, and Boynton (2003) with direction and speed. On this account, processing the speeds of the targets is more difficult when they move in different directions, because speed and direction may be processed by the same population of neurons (Maunsell & Newsome, 1987). If indeed speed cannot be entirely separated from direction, then comparisons of the speeds of two surfaces moving in different directions may be less accurate than if they move in the same direction.

Although it is still not clear whether the multiple-feature cost arises at the *selection* or *access* stage in Saenz, Buracas, and Boynton's (2003) study, other studies provide evidence that a multiple-feature cost can in some circumstances at least arise at the *access* stage. In the experiments of Lu and Itti (2005) and Sally, Vidnyansky, and Papathomas (2009), no distracters were presented, only targets, so presumably the targets were easily selected regardless of condition. In one case (Sally, Vidnyansky, & Papathomas, 2009), two intervals were presented during each trial, and two Gabors presented in each interval, one on each side. The participant's primary task was to judge in which of two intervals the Gabor on one side was tilted slightly from vertical. The secondary task was to judge the target on the other side. This secondary task could involve either the same feature value as that of the other side (judging which interval contained deviation from vertical) or involve a different feature value (judging which interval contained a target tilted slightly from horizontal). In the different-feature condition, orientation deviation thresholds were in some cases much worse than in the same-feature condition. Analogous results were found for judgments of speed (Lu & Itti, 2005; Sally, Vidnyansky, & Papathomas, 2009) and color (Sally, Vidnyansky, & Papathomas, 2009). All these studies demonstrated a performance difference between same-feature and different-feature conditions and the results were interpreted in terms of feature-based attention. However, by examining their experimental design with the selection/access theoretical framework, the apparent absence of any *selection* demand here suggests that the cost arose beyond the selection stage, at *access* or a later cognitive operation (such as comparing the feature values to a standard).

Here we sought to determine whether a multiple-feature cost could occur at the *selection* stage. We did this by manipulating the *selection* attribute across conditions while always using spatial period as the unrelated access attribute.

1.3. Mechanisms for multiple-feature costs

On a limited-resource theory of feature-based selection, splitting the resource between features yields a multiple-feature cost. However, a multiple-feature cost might also come from interference by distracters sharing the target features. Evidence for this is seen in Saenz, Buracas, and Boynton's (2003) study. Their first experiment included distracters superimposed on the targets, and when these were omitted in a subsequent experiment, the multiple-feature cost disappeared. The authors concluded that monitoring multiple features does not itself impede target perception, but rather competition among stimuli is the issue. Possibly, the spread of selection to distracters that share the target's features is the specific cause of the competition. Selection of, say, a downward-moving target in one location may have caused enhancement of the downward distracter in the other location. Perhaps it was the lack of this type of interference when the distracters were absent that eliminated the multiple-feature cost.

However, it would be premature to conclude that the multiple-feature cost arose from interference rather than resource splitting. One alternative is that when there was no superimposed distracter, the participants might have used space-based attention rather than feature-based attention to perform the task. In other words, they could just attend to the left and right locations regardless of the color similarity of the two targets. This could explain why the relative feature value (color) had no effect in that condition without the distracters.

To avoid this problem, in our experiments distracters were always present but varied in their relationship to the targets. Significant multiple-feature costs occurred only when the distracters shared selection features with the targets, suggesting the cost comes from the spread of featural selection to distracters. Because the experiments involved manipulating a selection attribute (color) that was very distinct from the access attribute (spatial period of a

grating), we conclude that the cost arises at selection rather than subsequent processing.

1.4. Error and lag

Previous studies documented multiple-feature costs in the form of performance errors, with monitoring more features yielding larger errors. This suggests that the representation of the monitored features is noisier or its signal is weaker. A complementary possibility is that monitoring multiple features might slow processing of the targets.

Slower processing can manifest as a greater temporal *lag*. That is, the participant might not be able to keep up with changing target characteristics and end up representing an older target state rather than its current state (Howard & Holcombe, 2008). Splitting attention among multiple objects can increase this lag (Howard & Holcombe, 2008). It remains an open question whether keeping the number of monitored objects constant, but varying the number of features monitored as we do here would increase the lags.

In one of the experiments documenting larger lags when more objects had to be monitored, Howard and Holcombe (2008) presented five Gabor patches whose spatial periods changed continuously. A subset of the five patches was designated as targets for monitoring, at the end one was queried, and participants attempted to report its final spatial period. Compared to one target, higher target numbers impaired reports of the spatial periods in two ways. First, the average size of the error was larger. Second, the spatial period reported was closer to that of the stimulus some time prior to the end of the trial than it was to its final state. This was the "perceptual lag". The lag was larger for higher target numbers: 140 ms for one target, 210 ms for two targets and 250 ms for four targets.

Adopting the lag measurement technique of Howard and Holcombe's (2008) study allows us to, for the first time as far as we know, examine the relationship of featural attention to processing lags, as well as to overall errors.

In Experiment 1 we presented targets defined by the same color or by different colors, asked the participants to report the spatial period, and found greater errors and lags when the targets were different colors. In Experiments 2 and 3 we manipulated the similarity between targets and distracters to examine how the distracters contributed to the multiple-feature cost.

2. Experiment 1

In each trial the participants were required to monitor the spatial periods of either one or two targets. In half of the trials with two targets, the targets were the same color (the "isochromatic-target condition") and in half of trials they were different colors (the "heterochromatic-target condition"). The two colors used were red and green. Each target was superimposed on a distracter grating of orthogonal orientation and the other color (green if the target was red and red if the target was green). Fig. 1 schematizes the two conditions.

As already found in Howard and Holcombe's (2008) study, we expected larger error and lag in the two-target condition than in the one-target condition. The main goal was to test whether similar effects appear when comparing *isochromatic-target* and *heterochromatic-target* conditions.

2.1. Method

All three experiments in this study conformed to the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans and were approved by the University of Sydney's ethics committee.

2.1.1. Participants

Eight participants (three female) participated in this experiment. All had normal or corrected-to-normal vision and two were authors (SYL and CJH).

2.1.2. Stimuli

Stimuli were presented on a Sony 21-in. screen, viewed from a distance of 45 cm. The screen resolution was 1024×768 pixels and the frame rate was 85 Hz. The experiment program was written in Python and used the VisionEgg library (Straw, 2008). The stimuli were two pairs of red–green superimposed grating patches. The radius of each patch was 2.1° of visual angle. One green (CIE *x*, *y* at the peak: 0.30, 0.60, luminance: 25.92 cd/m^2; trough: black) and one red (CIE *x*, *y* at the peak: 0.66, 0.32, luminance: 29.42 cd/m^2; trough: black) grating were superimposed in each of the two locations. To facilitate perceptual segregation of the superimposed gratings, one of the gratings at each location was oriented vertically and the other horizontally.

In the one-target condition, the participant attended to only one of the four gratings; in the two-target condition, the participant attended to one grating at each location. The relationships between the two pairs of gratings were determined by three factors of the experimental design: *arrangement, relative color* and *relative orientation*. For the factor of arrangement, the two pairs of gratings were arrayed either horizontally or vertically. In the horizontal arrangement, one was positioned directly left of fixation at an eccentricity of 4.77° of visual angle, and the other red–green superimposed grating pair was presented to the right of fixation at the same eccentricity. In the vertical arrangement, identical stimuli were used, but presented directly above and below fixation instead of to the left and to the right. The factor of relative color was relevant when there were two targets: the colors of the two targets could be the same or different, termed *isochromatic-target* or *heterochromatic-target* conditions, respectively. For the factor of relative orientation, the two target gratings' relative orientation was collinear, parallel or orthogonal. In the collinear condition, the orientations of the two target gratings were the same as their arrangement so they were oriented with the virtual line connecting them. For example, both targets are horizontally oriented in a horizontal array. In the parallel condition, the orientations of the two target gratings were the same, but different from their arrangement. For example, both targets might be horizontally oriented, but in a vertical array. In the orthogonal condition, the orientations of the two target gratings were orthogonal.

2.1.3. Procedure

There were 13 conditions in total: the one-target condition where only one target was monitored, and 12 two-target conditions constructed from a 2 (arrangement, i.e., horizontal or vertical) by 3 (relative orientation, i.e., collinear, parallel or orthogonal) by 2 (relative color, i.e., isochromatic-target or heterochromatic-target conditions) design. For each observer, the one-target conditions had 128 trials, in which 64 were in a horizontal arrangement and the other 64 in a vertical arrangement. The additional factors of absolute color, i.e., whether the target(s) was red or green, and absolute orientation, i.e., whether the target grating(s) was horizontal or vertical, were counterbalanced and are not counted among these conditions. For two-target conditions, as shown in Fig. 1, each of the two relative color conditions (isochromatic-target and heterochromatic-target conditions) contained 64 trials of collinear, 64 trials of parallel, and 128 trials of orthogonal target pairs (in order to equate the probabilities of all the absolute orientation combinations, there were horizontal/horizontal, vertical/vertical, horizontal/vertical, vertical/horizontal combinations for the orientations of the two targets, which will lead to more orthogonal trials than either collinear or parallel trials in terms of the relative orientation). Each of these

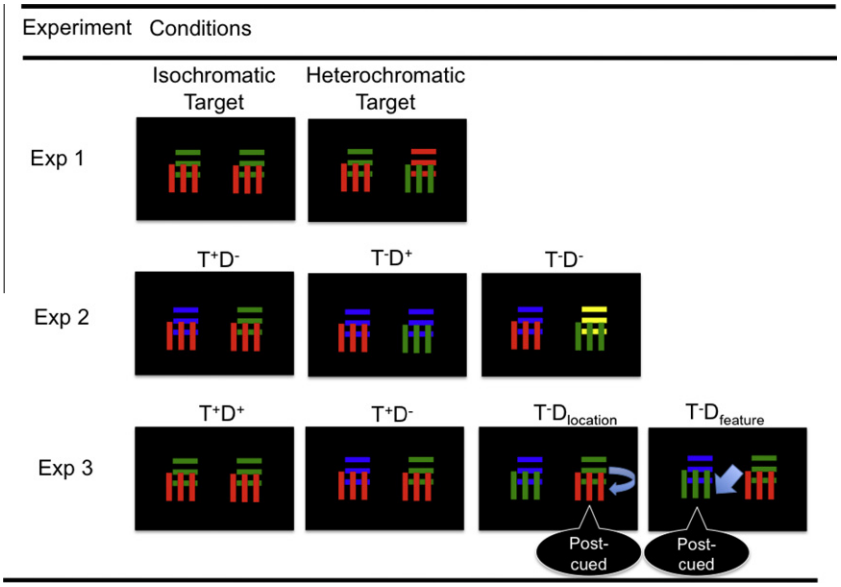

Fig. 1. A schematic illustration of different relationships between target (T) and distracter (D) colors in the three experiments. A plus (+) indicates isochromatic colors, e.g. T^+ means the targets were the same color, and T^- means the targets were differently colored. $D_{location}$ means that the target processing was interfered by the distracter at the same location, whereas $D_{feature}$ means that the target processing was interfered by the distracter with the same feature. In this figure the target is denoted by portraying in front of the distracter, but in the actual experiments the two stimuli were exactly superimposed with no spatial offset. Arrows in the bottom panel indicate potential interference.

conditions contained half horizontally aligned and the other half vertically aligned trials. The whole experiment required four sessions, and each session took approximately 40 min.

Each observer was given practice trials until they felt comfortable with the task. Each trial began with the central fixation point and one or two pre-cues to indicate the color(s) the observer should monitor in the corresponding location(s). The fixation point was white, with luminance 134 cd/m^2, and a radius of 0.22° of visual angle. The pre-cues were one or two disks, 1° in diameter, positioned in the direction of the indicated target, but with a larger eccentricity (9.54°). They were colored red or green to indicate which of the two gratings the observer should monitor on that side of the display. In the two-targets condition, the two targets were always on opposite sides of the display but were either the same (in the isochromatic-target condition) or different (in the heterochromatic-target condition) colors. Each trial began with the fixation point and the pre-cues being presented alone for 941 ms. Secondly, the two pairs of red–green superimposed gratings were added to the display. The pre-cue(s) and the fixation appeared together with the gratings for 1176 ms and then the pre-cues disappeared. The starting spatial period of each grating was a random value between 0.75 and 1.29 degrees per cycle (dpc). The four gratings changed their spatial periods independently and smoothly, ranging from 0.43 to 1.61 dpc.

"Velocity" will refer to the signed rate of change. The initial velocity of the spatial period for each grating in each trial was set randomly between −0.457 and 0.457 dpc/s. Zero velocity was avoided by adding a constraint that the magnitude of the velocity could never be less than 0.0914 dpc/s. The initial accelerations were randomly set between 0.388 and −0.388 dpc/s^2. Every 235 ms, the acceleration of each Gabor was reset to 0.388 or −0.388 dpc/s^2. If the rate of change (magnitude of the velocity) was smaller than 0.457 dpc/s, the absolute value of the acceleration was increased to 0.388 dpc/s^2. If either the minimal or maximal value of spatial period (0.43 and 1.61 dpc) was reached, the sign of the velocity was reversed. To prevent the gratings from changing too quickly to perceive their spatial frequency, if the rate of change exceeded 0.457 dpc/s the sign of the acceleration was reversed.

At a random time between 1824 and 6824 ms after the disappearance of the pre-cues, all the gratings disappeared. One of the two target gratings was post-cued by the return of one of the pre-cue markers. At the same time, a grating with the same color as the target appeared at center for the observers to adjust. Observers could use the up or down arrow key to adjust the spatial period of this grating (0.00645 dpc larger/smaller per button press), to match the final spatial period he or she had just seen. The left and right arrows could be used to adjust the period in finer steps (0.00215 dpc larger/smaller per button press). A diagram of this procedure is shown in Fig. 2.

2.2. Results

We firstly computed the *final error*, which is the difference between the spatial period indicated by the observer and the actual spatial period in the final frame. Outlier errors, as defined by being larger than third quartile or less than the first quartile by 1.5 times of the inter-quartile range were excluded from this and further analyses.

To determine the relationship between the spatial period reported and that of the stimulus at different times, "error curves" were plotted for each participant. For each trial, for each of the 150 frames of the stimulus prior to its disappearance, we calculated the absolute value of the difference between its spatial period and the value reported. These differences were averaged across trials to yield the error curve that plots error against time. The *minimal error* is the smallest error in the curve and the corresponding frame is that for which the participant's response most resembled the stimulus. The time of this frame relative to the disappearance of the stimulus is termed the *lag*. Consider the sample curve for the one-target condition shown for one participant in Fig. 3 (the dark solid line). The minimal error is 0.18 degrees per cycle and it occurred at 153 ms. This indicates that on average the participant reported not the final spatial period, but rather its value from 153 ms ago.

The heterochromatic condition (gray curve) in Fig. 3 yielded larger errors and this together with the flatness of the curve

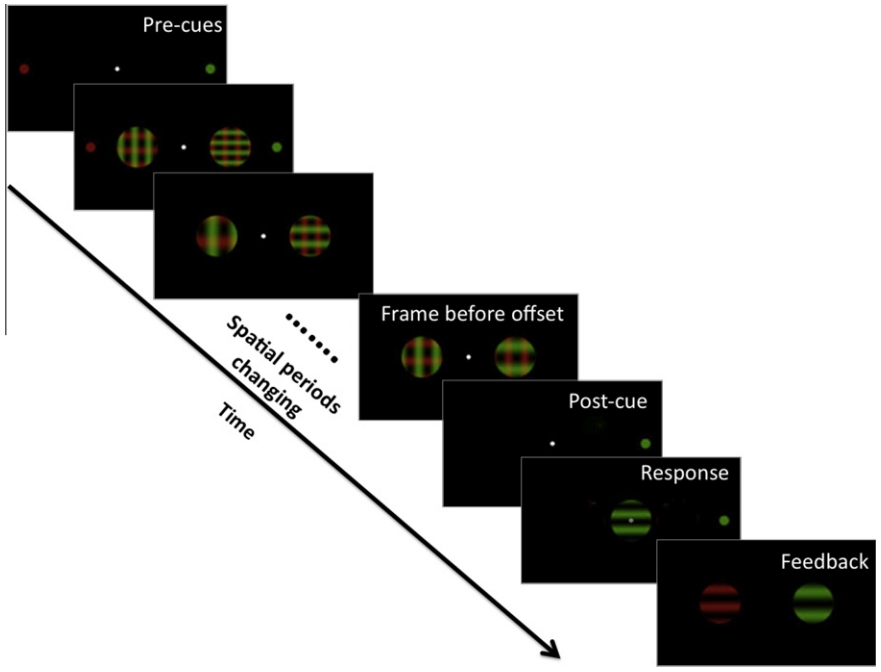

Fig. 2. Stimuli presented in a single trial. The white text on the graphs was not shown in the actual experiments. The spatial periods shown here are also enlarged for clarity.

suggests that the participants were guessing more frequently in that condition rather than responding with the stimulus value.

If the participants guessed on a large enough proportion of trials, the lag value calculated by our procedure would be meaningless, so we performed some analyses to investigate this.

2.2.1. Permutation tests

In our experiments, the lag values were inferred from the temporal locations where the minimal errors occurred. We should therefore confirm that the minimal error reflects participants' perception. The alternative we want to exclude is that it was a byproduct of noise or the participants' guessing strategy. The task design by itself does not guarantee a specific "chance" level of performance when participants guess. For one thing, the final value of the stimulus spatial period is not uniformly distributed across the possible values. Different guessing strategies would therefore yield different levels of performance. We used the participants' own responses as an estimate of their guessing distribution, by permuting them.

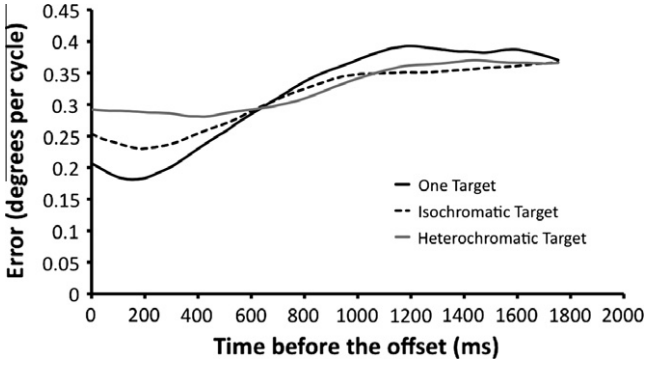

Fig. 3. Error curves in three different conditions from a representative participant SM. Each curve indicates the differences between the participant's reported spatial period and the physical spatial period of each frame before the stimulus offset. The black curve denotes the trajectory computed from the one-target condition. The dotted curve and gray curve denote the trajectories plotted from the isochromatic-target condition and heterochromatic-target condition, respectively. The data of all relative orientations and arrangements are collapsed here.

In the permutation tests, we randomly reassigned (permuted) the trial that each response was compared to. For example, the response from the first trial might be paired with the stimulus train from the 10th trial. We than compared the difference between the response and that unrelated stimulus train up to 150 frames before the offset, just as we did to get the standard error curves. From this permuted curve, a minimal error and a lag were obtained.

We then created 999 more permutations of the stimulus–response pairing, yielding 1000 minimal errors and lags. Repetitions among the 1000 permutations were allowed (the "with replacement" procedure) but no correct matching (e.g., the first response pairs with the first stimulus train) was allowed. The distribution of these 1000 minimal errors or lags was considered to be an approximation of the minimal errors or lags that would be obtained if the participants guessed.

Two kinds of statistical tests were performed with the minimal errors and lags: by-participant and by-condition.

The by-participant test allows us to confirm that the participant was not guessing on all trials and therefore that the minimal error value is not just a statistical fluctuation of a guessing distribution. For the by-participant test with the minimal error as the dependent variable, we used 12 minimal errors (one for each of the 12 two-target conditions they participated in) within each participant, and generated their permutation distributions. We than averaged these 12 distributions to estimate the sampling distribution under the hypothesis that the participant was guessing in all the conditions. We then compared the mean of the minimal error from the actual data with this guessing distribution, and computed the z-score and p-value of the actual data. If the p-value was larger than .05, the data from this participant would be excluded. The same logic and criterion were applied for the test with the lag as the dependent variable, in this and following experiments. The test results are shown in the upper part of Appendix A. All participants in this experiment passed the test.

The by-condition test allows us to confirm that the data from each condition did not result from all participant guessing and that the minimal error value was not just a statistical fluctuation of a

guessing distribution. For the by-condition test with the minimal error as the dependent variable, we used 8 minimal errors (one for each of the eight participants) within each condition, and generated their permutation distributions. Then we averaged these distributions, to estimate the sampling distribution under the hypothesis that the data from all the participants were results of guessing. We then compared the mean minimal error from the actual data with this guessing distribution. We rejected the null hypothesis that the mean minimal error in this condition is a result of all participants guessing, when the p is less than .05. The same logic was applied for the test with the lag as the dependent variable, in this and following experiments. The test results are shown in the lower part of Appendix A. In all the conditions in this experiment, the mean minimal errors and lags were significantly different from their permutation distributions, indicating that the lags and the minimal errors were not caused by random guessing.

2.2.2. Tests for errors and lags

After confirming the minimal errors and lags were not guessing artifacts, we conducted two basic analyses of the effect of condition on minimal error, final error, and lag. One was to examine the effect of number of targets. The second analysis was for the two-target condition and examined the effects of relative color, relative orientation, and arrangement.

To obtain the number-of-targets effect, we first averaged the data of the two-target conditions, and compared it with the one-target condition with paired t-tests. In the two-target condition the minimal error was .05 dpc ($t(7) = 5.12$, $p < .001$) larger than that for the one-target condition, and the final error was .06 dpc ($t(7) = 4.86$, $p < .001$) larger. The lag in the two-target condition was 125 ms larger than in the one-target condition ($t(7) = 2.74$, $p = .01$).

As will be reported later in this section, the two-target isochromatic condition yielded higher performance than did the heterochromatic condition. But the one-target condition yielded even higher performance. Comparing it to the two-target isochromatic condition, the minimal error was .04 dpc ($t(7) = 3.17$, $p = .008$) smaller, the final error was .05 dpc smaller ($t(7) = 3.15$, $p = .008$), and the lag 106 ms smaller ($t(7) = 1.87$, $p = .05$). Together, these results indicate that when observers monitored an additional grating, both the error and the lag were larger, consistent with Howard and Holcombe's (2008) results.

To test for differences among the two-target conditions, relative color, relative orientation, and arrangement were entered as independent factors in a three-factor analysis of variance. Before running the ANOVA, we used Levene's test (Levene, 1960) to examine whether the variance in each condition was equal. In this and subsequent experiments, we conducted Levene's test on the raw data and its square root, and chose the one whose variances are more homogeneous for further analyses.

The minimal and final errors for each condition are plotted in Fig. 4. Data from different relative orientations and arrangements were collapsed for readability in the plot, but in the statistical analyses these factors were included. For the minimal error and the final error, the square root transformed data (minimal error: $W = 1.833$, $p = .06$; final error: $W = 3.26$, $p < .01$) had more homogeneous variance than the raw data (minimal error: $W = 1.835$, $p = .06$; final error: $W = 3.54$, $p < .01$), so we used the square root values to run ANOVAs. The minimal error was significantly larger in the heterochromatic-target condition than in the isochromatic-target condition by .03 dpc ($F(1,7) = 106.75$, $p < .001$), and the final error was .04 dpc larger ($F(1,7) = 55.53$, $p < .001$). This was our main interest, that targets defined by different colors yielded worse performance than targets of the same color.

Relative orientation ($F(2,14) = 5.13$, $p = .02$) also had a significant effect in that minimal error was larger by .02 dpc in the orthogonal condition than in the collinear condition, but the effect on final error

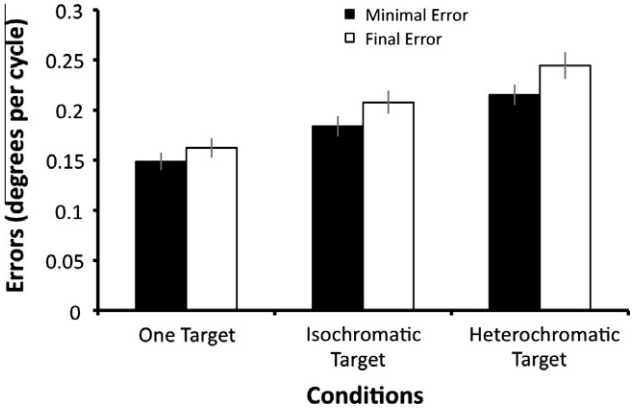

Fig. 4. Minimal and final errors of Experiment 1. Means across subjects. Error bars show one standard error of variability.

was not significant ($F(2,14) = 1.58$, $p = .24$). Regarding arrangement, there was no significant effect on the minimal error ($F(1,7) = 3.03$, $p = .13$) but a significant effect on the final error ($F(1,7) = 6.87$, $p = .03$), in which the final errors in the vertical arrangement were .01 dpc larger than those of the horizontal arrangement.

There were no significant interactions among the three factors for the errors: minimal error (relative color and relative orientation: $F(2,14) = 0.25$, $p = .78$; relative color and arrangement: $F(1,7) = 0.32$, $p = .59$; relative orientation and arrangement: $F(2,14) = 0.06$, $p = .94$; relative color, relative orientation, and arrangement: $F(2,14) = 0.75$, $p = .49$); final error (relative color and relative orientation: $F(2,14) = 0.21$, $p = .82$; relative color and arrangement: $F(1,7) = 1.37$, $p = .28$; relative orientation and arrangement: $F(2,14) = 0.67$, $p = .53$; relative color, relative orientation, and arrangement: $F(2,14) = 0.70$, $p = .51$).

Rather than relying entirely on the ANOVA for our main comparison, we also performed a t-test after collapsing across the arrangement and orientation factors. The t-test, like the ANOVA reported above, indicates that performance with isochromatic targets is better than performance with heterochromatic targets, for both the minimal errors ($t(7) = 10.43$, $p < .001$) and final errors ($t(7) = 7.09$, $p < .001$).

The lag results are shown in Fig. 5, with different relative orientations averaged for readability. Levene's test indicated that the lags violate the assumption of homogeneity of variance ($W = 2.24$, $p = .02$), which was remedied by taking the square root (resulting in Levene's test $W = 0.87$, $p = .58$). The transformed values were entered into a 2 (relative color) by 3 (relative orientation) by 2 (arrangement) ANOVA. The interaction of arrangement and relative color was significant ($F(1,7) = 5.64$, $p = .049$). Simple main effect analyses showed that in the horizontal arrangement, the lag in the heterochromatic-target condition was larger than that in the isochromatic-target condition by 125 ms ($F(1,7) = 6.32$, $p = .04$). When the gratings were vertically arrayed however, instead of a multiple-feature cost a non-significant trend was present for a multiple-feature benefit of 48 ms ($F(1,7) = 0.72$, $p = .43$). There was no significant effect of relative orientation ($F(2,14) = 0.64$, $p = .54$), and no other significant interactions were found (relative orientation and relative color: $F(2,14) = 0.57$, $p = .58$; relative orientation and arrangement: $F(2,14) = 0.44$, $p = .65$: relative orientation, relative color and arrangement: $F(2,14) = 0.52$, $p = .61$).

In addition to the analyses of relative color and relative orientation, we also examined whether the absolute color (whether the target was green or red) and absolute orientation (whether the target grating was horizontal or vertical) of targets influence performance. We again used Levene's test to decide whether to use the square root transformed or the raw data. For the three

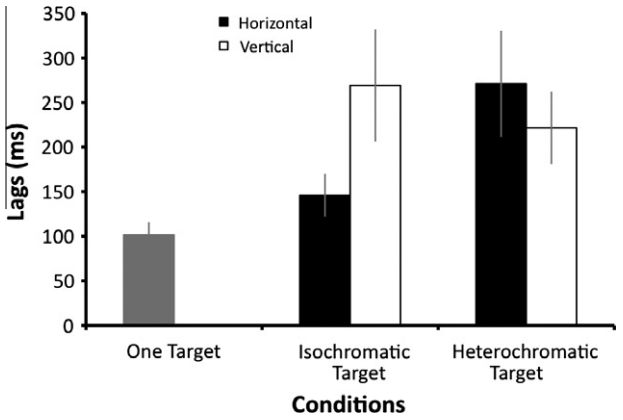

Fig. 5. Lags of Experiment 1. Means across subjects. Error bars show one standard error of variability.

dependent variables, we used the raw data (minimal error: $W = 0.295$, $p = .829$; final error: $W = 0.91$, $p = .45$; lag: $W = 0.75$, $p = .53$) rather than the transformed data (minimal error: $W = 0.297$, $p = .827$; final error: $W = 0.93$, $p = .44$; lag: $W = 1.40$, $p = .26$). There was no significant effect of absolute color on the minimal error ($F(1,7) = 0.003$, $p = .96$), final error ($F(1,7) = 0.31$, $p = .59$), or lag ($F(1,7) = 2.18$, $p = .18$). The vertical target yielded marginally worse performance than the horizontal target on minimal error ($F(1,7) = 4.83$, $p = .06$), final error ($F(1,7) = 4.97$, $p = .06$) but there was no apparent effect on lag ($F(1,7) = 0.002$, $p = .97$). Neither was there a significant interaction of absolute color and absolute orientation on minimal error ($F(1,7) = 0.09$, $p = .77$), final error ($F(1,7) = 1.05$, $p = .34$) or lag ($F(1,7) = 2.82$, $p = .14$).

2.3. Discussion

Manipulating the similarity of the target colors to be selected, we found a substantial cost of selecting different features. These results indicate that the multiple-feature cost can be caused by a selection problem, as we changed only the selection attribute, not the access attribute (here, spatial period). When targets were horizontally arrayed, the requirement to attend to different colors simultaneously yielded a longer perceptual lag. However, this lag effect was not apparent when the targets were vertically arrayed. Possible explanations will be discussed in Section 5.

A potential explanation for the multiple-feature cost for selection is that simply splitting attention among features both slows target processing and reduces its quality, due to the limited resource available. However, another possibility for this multiple-feature cost is that it might reflect unwanted distracter processing.

In the heterochromatic-target condition, because the distracters were the same colors as the targets, feature-based attention may have caused more processing of them, yielding more interference. In other words, the cost may have resulted from a difficulty attending to an item of one color in one location while ignoring an item of the same color in another location. We will refer to this as "feature-based interference". To test this explanation, we conducted Experiment 2. In this experiment, the distracters never shared a color with any of the targets.

3. Experiment 2

The multiple-feature cost in Experiment 1 may have resulted from a limit on the resources of feature-based attention, such that when two feature values are selected, each receives fewer resources than if only one is selected. According to this limited-resource theory, when monitoring more colors, effectiveness of attentional selection should decrease. Another possible explanation of the multiple-feature cost arises from the dual role of each color as both target and distracter. For example, in the heterochromatic-target condition in Experiment 1, the color red served as the target at one location and as the distracter at the other location. This might have induced more distracter interference, because the distracter at each location also had the same color as the target at the opposite location, yielding feature-based interference.

In this experiment, the distracters did not share the same color as the target. If the multiple-feature cost is similar to that of Experiment 1, then the cost should be attributed simply to splitting attention among two target colors; if the multiple-feature cost is attenuated or disappears, it should be attributed to feature-based interference.

3.1. Method

3.1.1. Participants

Of the eight participants (three females) in this experiment, six had participated in Experiment 1, including two of the authors (SYL and CJH).

3.1.2. Stimuli and procedure

The number of targets was always two. There were three possible relationships between the colors of the target and distracters (Fig. 1): Isochromatic-target heterochromatic-distracter condition (denoted as T^+D^-) refers to the condition where the two targets were the same color (red, green, blue, or yellow) but the distracters were two other colors (so in total three colors were used). In the heterochromatic-target heterochromatic-distracter (denoted as T^-D^-) condition, all four gratings in the display were of different colors. In this case the total color number (four) exceeds that in the T^+D^- condition (three), so we also included another condition, heterochromatic-target isochromatic-distracter condition (denoted as T^-D^+), meaning the two targets were of different colors but the two distracters were of the same color without any overlapping with the target color. The critical issue was whether the T^- conditions would lead to poorer performance than the T^+ condition, consistent with the limited-resource theory. Alternatively, a difference in target color might only be harmful if distracters share the target colors, in which case no heterochromatic-target costs should be evident in this experiment. In addition to the three relative color conditions, we used the same manipulations of relative orientation and arrangement as in Experiment 1. For each participant, each relative-color condition had 192 trials, composed of 48 collinear trials, 48 parallel trials and 96 orthogonal trials. Each relative-orientation condition was further composed of half vertical and half horizontal arrangement trials.

The stimuli were presented on the same monitor as Experiment 1. In addition to the red and green gratings as shown in Experiment 1, we included a yellow (CIE x, y at the peak: 0.47, 0.48, luminance: 83.08 cd/m^2; trough: black) and a blue (CIE x, y at the peak: 0.16, 0.07, luminance: 15.27 cd/m^2; trough: black) grating as potential targets or distracters. As a pilot study using the same cue size as in Experiment 1 suggested that discriminating among these four cue colors in the periphery was sometimes difficult, we enlarged the size of the pre-cue to 1.67° of visual angle. The luminance values of the pre-cues were the same as those of the peak value of the grating of each color.

3.2. Results

There was little or no effect of relative color on performance. Indeed, the only significant difference was a three-way interaction

on the minimal error, one that does not appear relevant to our hypotheses.

3.2.1. Permutation tests

The by-participant tests showed that each participant's minimal errors and lags were significantly different than the guessing distribution estimated with the permutation procedure. The by-condition test further showed that in each condition, the minimal errors and lags were different from the permutation distributions (see Appendix B). See Experiment 1 for full explanation of the calculation.

3.2.2. Tests for errors and lags

Fig. 6 shows the results after averaging across different relative-orientation and arrangement conditions. Levene's test for homogeneity of variance suggested that for the minimal error, the raw data ($W = 1.0$, $p = .47$) be used instead of the transformed data ($W = 1.16$, $p = .31$) and for the final error and the lag, the transformed data (final error: $W = 1.35$, $p = .17$; lag: $W = 1.07$, $p = .39$) be used instead of the raw ones (final error: $W = 1.40$, $p = .15$; lag: $W = 1.24$, $p = .25$). There was a three-way interaction between the arrangement, relative color and relative orientation on the minimal error ($F(4,28) = 3.59$, $p = .02$). We tested the simple main effect of relative color of each individual combination of arrangement and relative orientation. There were no significant effects of relative color in the horizontal-collinear ($F(2,28) = 1.86$, $p = .17$), horizontal-parallel ($F(2,28) = 0.87$, $p = .43$), horizontal-orthogonal ($F(2,28) = .03$, $p = .97$), vertical-collinear ($F(2.28) = 1.66$, $p = .21$), and vertical-orthogonal ($F(2,28) = 0.21$, $p = .81$) conditions. There was a significant effect of the relative color in the vertical–parallel condition ($F(2,28) = 3.98$, $p = .03$), in which the minimal error values in the T^+D^-, T^-D^+ and T^-D^- conditions were 0.22, 0.25 and 0.20 dpc. Tukey's HSD test showed the significant difference only existed between T^-D^+ and T^-D^- conditions. In both of those conditions, the targets were heterochromatic so it was irrelevant to our main interest of the comparison of isochromatic-target and heterochromatic-target conditions. To summarize, no cost for differently-colored targets is seen in the minimal errors. The summary for the final errors is the same, as detailed next.

The final errors (Fig. 6) in the T^+D^-, T^-D^+ and T^-D^- conditions were 0.24, 0.25 and 0.24 dpc. Further analysis showed no significant effect among these three conditions ($F(2,14) = 0.46$, $p = .64$). There was a significant effect of relative orientation ($F(2,14) = 6.38$, $p = .01$), in which the error in the collinear condition was .02 dpc lower than that in the parallel condition, and was .01 dpc lower than that in the orthogonal condition. There was no significant effect of the arrangement ($F(1,7) = 2.79$, $p = .14$). There were no significant interactions (relative color and relative orientation: $F(4,28) = .77$, $p = .55$; relative color and arrangement: $F(2,14) = 0.10$, $p = .91$; relative orientation and arrangement: $F(2,14) = 0.64$, $p = .54$ relative color, arrangement, and relative orientation: $F(4,28) = 2.24$, $p = .09$).

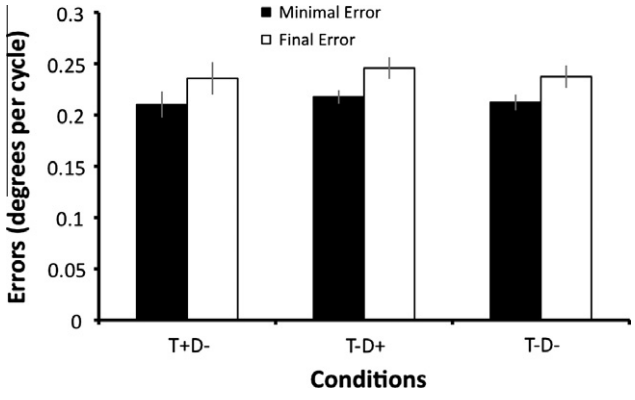

Fig. 6. Minimal and final errors of Experiment 2. Means across subjects. Error bars show one standard error of variability.

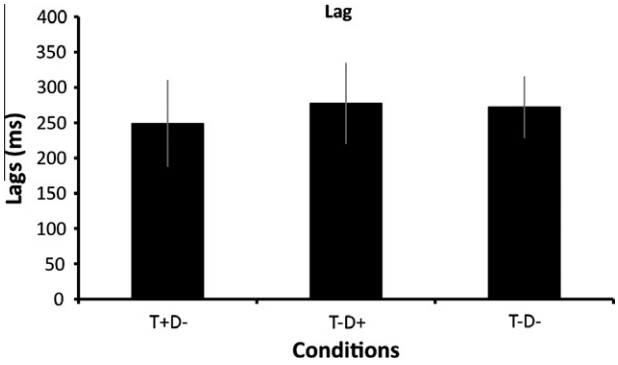

Fig. 7. Lags of Experiment 2. Means across subjects. Error bars show one standard error of variability.

The lags (Fig. 7) in the T^+D^-, T^-D^+ and T^-D^- conditions were 249, 277 and 272 ms. An ANOVA indicated no significant main effects (arrangement: $F(1,7) = .22$, $p = .65$; relative orientation: $F(2,14) = 1.81$, $p = .20$; relative color: $F(2,14) = .23$, $p = .80$). There were no significant interactions (arrangement and relative orientation: $F(2,14) = 2.35$, $p = .13$; arrangement and relative color: $F(2,14) = .58$, $p = .57$; relative orientation and relative color: $F(4,28) = .86$, $p = .50$; arrangement, relative orientation and relative color: $F(4,28) = 2.34$, $p = .08$).

We also analyzed the effects of absolute colors and orientation. We chose the transformed data (minimal error: $W = 1.80$, $p = .11$; lag: $W = 0.90$, $p = .52$) over the raw data (minimal error: $W = 1.86$, $p = .09$; lag: $W = 1.06$, $p = .40$) for the minimal error and lag, and the raw data ($W = 1.82$, $p = .10$) over the transformed data ($W = 2.02$, $p = 0.07$) for the final error for further analyses. There was no significant effect of absolute color on minimal error ($F(3,21) = 0.35$, $p = .79$), final error ($F(3,21) = 0.41$, $p = .75$) or lag ($F(3,21) = 2.23$, $p = .11$); no significant effect of absolute orientation on minimal error ($F(1,7) = 2.71$, $p = .14$), final error ($F(1,7) = 0.54$, $p = .49$) or lag ($F(1,7) = 0.03$, $p = .86$); no significant effect of interaction of the two factors on minimal error ($F(3,21) = 1.15$, $p = .35$), final error ($F(3,21) = 0.87$, $p = .47$) or lag ($F(3,21) = 0.14$, $p = .93$).

3.3. Discussion

As discussed earlier, the multiple-feature cost in Experiment 1 might have been due to splitting attention between two colors, or alternatively to feature-based interference from the distracters. When we used different sets of colors for targets and distracters in Experiment 2, no significant multiple-feature cost was observed. For minimal error in Experiment 2, comparing the isochromatic-target condition to the average of the heterochromatic-target conditions, the non-significant trend present (.005 dpc) was only 15% the size of the corresponding effect in Experiment 1 (.03 dpc). It appears that the splitting hypothesis cannot fully account for the multiple-feature cost in Experiment 1. Instead, the effect of multiple features may have arisen from interference by distracters sharing the target colors.

4. Experiment 3

In Experiment 2 the distracters did not share colors with the targets and no significant multiple-feature cost was observed. This suggests that feature-based interference from the distracters contributed to the multiple-feature cost seen in Experiment 1. This

feature-based interference in the heterochromatic-target condition of Experiment 1 could arise from two sources: same-location or same-feature interference. Consider the red target – one possible source of interference is from the green distracter at the same location, whose processing might be enhanced because it shares the color of the other target (same-location interference). The other possible source of interference is the red distracter (same feature) at the opposite location.

The current experiment used color combinations for targets and distracter locations designed to examine separately the two types of possible interference, same-location and same-feature. For some conditions of Experiment 3, a target shared its color with the distracter in the other location and in some it did not.

4.1. Method

4.1.1. Participants

Eight participants (three females) took part in the experiment, including the authors SYL and AOH.

4.1.2. Stimuli and procedure

Four different relative colors of target and distracter were employed in this experiment, involving only red, green and blue. Two of the relative colors were termed isochromatic-target conditions (the left two graphs in the row of Experiment 3 in Fig. 1) and the other two were heterochromatic-target conditions (the right two graphs in the row of Experiment 3 in Fig. 1). In the isochromatic-target conditions, the distracters could be isochromatic (T^+D^+) or heterochromatic (T^+D^-). In the heterochromatic-target conditions, one of the distracters had the same color as one of the targets but the other did not. For one target, the distracter might cause interference because it shared its location of the target but not its color (same-location interference), so the condition where this target is post-cued is denoted $T^-D_{location}$. For the other target, the distracter could cause interference because it shared its color but not its location (same-feature interference), and the condition where this target is post-cued is denoted $T^-D_{feature}$ condition. The type of interference that manifests on that trial would depend on which target was post-cued, as illustrated in Fig. 1, where the arrows indicate the potential interferences.

The possibilities for relative orientation were the same as those in Experiment 1 and 2—three relationships between two targets were used on different trials: collinear, parallel, or orthogonal. The two pairs of gratings were always horizontally arrayed in this experiment, where one target was presented directly to the left of fixation and the other directly to the right.

There were 96 trials in each condition of the four target–distracter relative colors. Among the 96 trials, in 48 of them the relative orientations were orthogonal, 24 of them were collinear, and 24 of them were parallel. The experiment was divided into two sessions and each session lasted 30–40 min.

4.2. Results

4.2.1. Permutation tests

The by-participant test is shown in the upper part of Appendix C. For one participant (EK), the minimal error and lag were not significantly different from the permutation distribution so her data were excluded from the analyses. For the remaining seven participants, we ran the by-condition permutation test and in all conditions, the minimal errors from the actual data all satisfied our criterion, as shown in the lower part of Appendix C.

4.2.2. Tests for errors and lags

The results of Levene's test caused us to use the raw data (minimal error: $W = 1.41$, $p = .19$; final error: $W = 3.19$, $p = .001$) rather than the transformed data (minimal error: $W = 1.44$, $p = .18$; final error: $W = 3.25$, $p = .001$) for minimal error and final error, and the transformed data ($W = 1.49$, $p = .15$) rather than the raw data ($W = 3.91$, $p < .001$) for the lag.

No statistically significant interference effects were observed in this experiment. The data were subjected to a two-factor 4 (relative color) by 3 (relative orientation) ANOVA. For the minimal error (Fig. 8), the errors in the T^+D^+, T^+D^-, $T^-D_{location}$ and $T^-D_{feature}$ conditions were 0.20, 0.20, 0.21, and 0.20 dpc (no significant difference, $F(3,18) = 0.15$, $p = .93$). The relative orientation factor also made no significant difference ($F(2,12) = 1.22$, $p = .33$), and no interaction was observed ($F(6,36) = 0.84$, $p = .55$). These factors also apparently had no effect on the final error (Fig. 8); for the T^+D^+, T^+D^-, $T^-D_{location}$ and $T^-D_{feature}$ conditions the final errors were 0.23, 0.23, 0.23, and 0.23 dpc (no significant difference, $F(3,18) = 0.08$, $p = .97$). In addition, no significant effect of relative orientation ($F(2,12) = 0.41$, $p = .67$), or interaction of the two factors ($F(6,36) = 0.42$, $p = .86$) was observed.

With perceptual lag the dependent variable, relative color and relative orientation again had little to no effect (Fig. 9). The lags in the T^+D^+, T^+D^-, $T^-D_{location}$ and $T^-D_{feature}$ conditions were 248, 324, 145, and 254 ms, and no significant effect was observed according to the two-factor ANOVA ($F(3,18) = 1.89$, $p = .17$). No effect of relative orientation ($F(2,12) = 0.56$, $p = .58$) or interaction of the two ($F(6,36) = 0.34$, $p = .91$) was observed.

We also analyzed the effects of absolute color and orientation. For all three dependent variables, their transformed values (minimal error: $W = 1.30$, $p = .28$; final error: $W = 1.76$, $p = .15$;

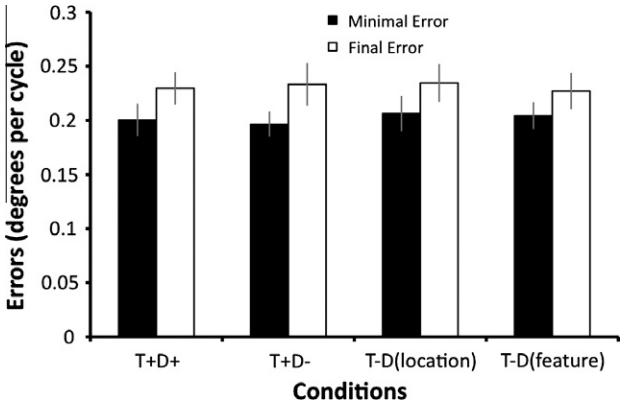

Fig. 8. Minimal and final errors of Experiment 3. Means across subjects. Error bars show one standard error of variability.

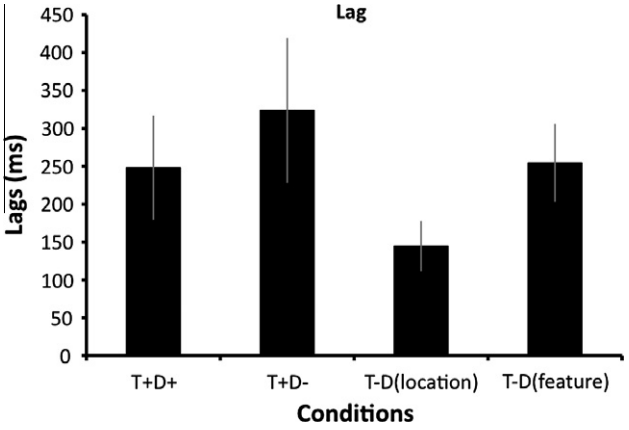

Fig. 9. Lags of Experiment 3. Means across subjects. Error bars show one standard error of variability.

lag: $W = 1.33$, $p = .27$) were used instead of the raw values (minimal error: $W = 1.38$, $p = .26$; final error: $W = 2.22$, $p = .07$; lag: $W = 2.39$, $p = 0.06$). There was no significant effects of absolute color on minimal error ($F(2,12) = 0.09$, $p = .92$), final error ($F(2,12) = 0.19$, $p = .83$), or lag ($F(2,12) = 3.35$, $p = .07$); no significant effect of relative orientation on minimal error ($F(1,6) = 0.04$, $p = .85$), final error ($F(1,6) = 0.24$, $p = .64$) or lag ($F(1,6) = 1.44$, $p = .27$); no interaction between the two factors on minimal error ($F(2,12) = 0.38$, $p = .69$), final error ($F(2,12) = 0.72$, $p = .51$) or lag ($F(2,12) = 0.08$, $p = .92$).

4.3. Discussion

We defined same-location interference as interference from a distracter at the same location whose color was attended at the other location, and same-feature interference as interference from a distracter at the other location that shared the target's color. In this experiment, neither type of interference should have occurred in the T^+D^- and T^+D^+ conditions whereas in the other conditions, the target queried on each trial was vulnerable to either same-location interference or same-feature interference, but not both.

The non-significant difference in minimal error between the isochromatic-target conditions (average across T^+D^- and T^+D^-) and heterochromatic-target conditions (average across $T^-D_{location}$ and $T^-D_{feature}$) was .007 dpc, suggesting a small penalty for the heterochromatic conditions may be present. For the lag, however, the insignificant trend was in the opposite direction, favoring the heterochromatic-target condition by 85 ms. In Experiment 1 where both distracters shared color with the targets the advantage for the isochromatic-target conditions was .03 dpc for minimal error and 125 ms for lag. The two kinds of interference may together have impeded the processing quality and time to yield the multiple-feature cost in Experiment 1. Either one alone was insufficient to induce a significant cost in the error or lag.

We cannot rule out small non-significant interference effects in both the $T^-D_{location}$ and $T^-D_{feature}$ conditions that may combine additively to yield the interference effect in Experiment 1. But the pattern of results here raises the possibility that the combination of common feature and common location had a super-additive effect.

5. General discussion

Monitoring multiple features has a cost (Lu & Itti, 2005; Saenz, Buracas, & Boynton, 2003; Sally, Vidnyansky, & Papathomas, 2009). The cost may be an increased difficulty of selection, such as in segregating targets from non-targets, or in a post-selection difficulty of appropriately processing the targets' access features. As it appears that multiple-feature costs can occur even when there is no selection problem (Lu & Itti, 2005; Sally, Vidnyansky, & Papathomas, 2009), indicating a multiple-feature cost at the access stage, our first goal was to explore whether this cost would still be observed with a manipulation of feature similarity that should affect only the selection stage. This was accomplished by using distinct selection and access attributes. The resulting cost was substantial (Experiment l). We also discovered that the cost was associated with a larger perceptual lag.

Rather than being caused by splitting selection between two different features, the results of Experiments 2 and 3 suggest that the cost was a result of how selection of multiple features enabled interference from distracters sharing those features. Three possible mechanisms for our results are proposed in the following paragraphs.

One possible mechanism is automatic spreading of feature-based selection (Saenz, Buracas, & Boynton, 2003; Serences & Boynton, 2007; Treue & Martinez-Trujillo, 1999) to all stimuli possessing the selection feature of the target. In the heterochromatic-target condition of Experiment 1, when the observer was attending to a red target at one location and a green target at the other location, spreading of feature-based attention will enhance processing of the distracters with the same colors as the targets. This could result in interference with target processing and likely yields the larger error. In Experiment 2, when the distracters did not have the colors of the targets, spreading of feature-based attention would not result in enhancement to the distracters, consistent with our finding of no significant multiple-feature cost. The result of Experiment 3 suggests that the two kinds of distracter-to-target interference may be super-additive.

A critical part of this automatic spreading account is the interference from distracters to targets. The existence of this kind of interference is compatible with various models, including the normalization model of attention (Reynolds & Heeger, 2009). In this model, the activation of a neuron is the excitatory component from its preferred stimulus, divided by a suppressive component from a group of other neurons, which respond to neighboring stimuli. Both the excitatory and the suppressive components can be modulated by attention. In the case of our study, the activation for each target should reflect an excitatory component from the neurons responding to the targets, divided by the suppression from neurons that respond to the distracters. In the heterochromatic-target condition in Experiment 1, when the distracters shared the same colors with the targets, this suppressive component would be strengthened because attention spread to them, consistent with the multiple-feature cost observed. In the heterochromatic-target conditions in Experiments 2 and 3, the distracters did not totally overlap with the target colors, so the suppressive effect should be weaker, consistent with the absence of a significant multiple-feature cost.

A second possible mechanism is that the multiple-feature cost reflects a difficulty with maintaining an attentional set to select a particular color in one location but not others. To avoid a multiple-feature cost when a distracter is present with a target color, observer's attention must be contingent on both color and location. In the heterochromatic-target condition in Experiment 1, when the targets were red on the left and green on the right, the participants might have to maintain control settings of 'red', 'green', 'right', 'left', and additionally two bindings of 'red and left' and 'green and right'. So the cognitive attentional set may require maintenance of up to six units of information. As there were no distracters with the target colors in Experiment 2, participants could set their attention to simply activate the target colors, without bothering with location. In Experiment 3, although one of the distracters shared one of the target colors in the heterochromatic-target conditions, it might still be easier for the participants than that in Experiment 1. For example, if the targets are red on the left and green on the right, and one of the distracters is green on the left, participants might need to use the information of 'green', 'right', and the binding of 'green and right' so there are three units of information to avoid the green target being confused with the green distracter. For the color of red, participants do not need to use any location information so there are only four units of information (three units of information for the green target and 1 unit for the red target). In comparison to six units of information in Experiment 1, four units of information may still be within a certain limit of attentional setting so no significant cost would be observed.

A third possible mechanism is forgetting. Participants may be more likely to forget which Gabors were the targets in the heterochromatic-target condition than in the isochromatic-target condition. Assuming that this forgetting should be greater for longer trial durations, for each participant we computed the correlation between the error magnitude and the trial duration in Experiment 1, and found only a trend in the opposite direction predicted by the

hypothesis (which was weak and non-significant, $r = -0.005$ between the two factors, $t(7) = 0.32$, $p = .76$.) Also the memory demand was very limited, so we believe the forgetting hypothesis is unlikely to explain the result of Experiment 1.

A puzzling interaction between arrangement and relative color was found in Experiment 1- greater lags for heterochromatic targets were observed with the horizontal arrangement but the lag was uniformly long in the vertical arrangement. Further analyses revealed that the lag was smallest in the horizontally arrayed isochromatic-target condition. This could be related to the separate-resource hypothesis, indicating that each hemisphere has its own independent resource for processing the stimulus in the contralateral visual field (Alvarez & Cavanagh, 2005; Luck et al., 1989). When the two isochromatic targets are horizontally arrayed, the separate hemispheric resources monitor the targets in parallel to a greater extent. However, if when the colors of the two targets differ, it is more likely that attention needs to switch between the different colors, this would explain the greater lag. In the vertical arrangement even in the isochromatic-target condition a certain amount of switching is required, because the two targets are processed in the same hemisphere. This might explain why the lags were long in both the isochromatic-target and heterochromatic-target conditions.

Alternatively, the interactive effects of arrangement and relative color on lag might be related to the connections of the corpus callosum, which preferentially connect horizontally-displaced retinal locations equidistant from the vertical meridian (Engel et al., 1991; Nowak et al., 1995) and seems to have behavioral consequences (Benmussa et al., 2011). This might lead to better performance when stimuli were bilaterally presented. If the effective connectivity was modulated by color similarity, it could account for the interaction. In the vertical condition, the lack of callosal connection between the upper and lower hemispheres may lead to larger errors and longer lags. However, this is very speculative, and more data would be required to support this proposed mechanism.

A novel finding from this study is the multiple-feature cost in lag. Behavioral costs from multiple feature monitoring have been demonstrated with larger errors or thresholds (Lu & Itti, 2005; Saenz, Buracas, & Boynton, 2003; Sally, Vidnyansky, & Papathomas, 2009), which are related to the difference between participants' reports and the physical values of the stimuli. These previously-published results may result from coarser or noisier representations of the stimuli. In the present study we have also demonstrated a temporal cost, meaning a more lagged temporal representation of the stimuli.

Theories of attention ought to be elaborated to explain the present lag findings. We will consider both serial and parallel processing theories. Serial theories have the advantage that lags and their increase with processing difficulty are expected as a direct consequence of the theory's core idea. When two targets must be processed, each will be processed only half as often as when only one target must be processed, and the participant's report will therefore be more out of date (greater lag). In the heterochromatic condition, it may take longer to process each target or to suppress the distracter interference, which will further increase the lag. Parallel theories can add a new assumption of general slowing of processing when load is higher. We have not seen substantially slowed processing in the neural responses typically discussed as support for theories like the normalization theory of attention (Reynolds & Heeger, 2009), so these theories may need to be expanded to encompass higher-level processing.

Because we used color alone to probe feature-based attention and multiple-feature cost, further studies are required to know whether these results generalize to other attributes.

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Appendix A

Minimal errors or lags from Experiment 1 and their permutation distributions were averaged across conditions (in the by-participant test) or participants (in the by-condition test). The differences between the means of the data and the means of the averaged permutation distributions are listed in the 'data mean–permutation mean' column. The corresponding *z*-scores and *p*-values of these differences are listed in the right 2 columns.

Method	Participant	Data mean–permutation mean (dpc)	*z*	*p*
By participant Minimal error	SM	−0.05	−7.19	<.001
	SYL	−0.14	−18.75	<.001
	WYC	−0.14	−17.99	<.001
	LH	−0.07	−10.53	<.001
	CJH	−0.09	−15.37	<.001
	KC	−0.10	−14.27	<.001
	CK	−0.17	−20.60	<.001
	VX	−0.06	−9.63	<.001
By participant Lag	SM	−582	−3.50	<.001
	SYL	−797	−4.52	<.001
	WYC	−732	−4.50	<.001
	LH	−599	−3.51	<.001
	CJH	−737	−5.19	<.001
	KC	−579	−3.41	<.001
	CK	−719	−4.06	<.001
	VX	−450	−3.37	<.001

Appendix A (*continued*)

Method	Number of targets	Arrangement	Relative orientation	Relative color	Data mean–permutation mean (dpc)	*z*	*p*
By condition	1				−0.19	−35.99	<.001
Minimal error	2	Horizontal	Collinear	Isochromatic	−0.14	−13.85	<.001
		Horizontal	Collinear	Heterochromatic	−0.09	−10.18	<.001
		Horizontal	Parallel	Isochromatic	−0.13	−13.11	<.001
		Horizontal	Parallel	Heterochromatic	−0.08	−8.05	<.001
		Horizontal	Orthogonal	Isochromatic	−0.11	−16.94	<.001
		Horizontal	Orthogonal	Heterochromatic	−0.09	−13.05	<.001
		Vertical	Collinear	Isochromatic	−0.12	−13.02	<.001
		Vertical	Collinear	Heterochromatic	−0.09	−9.71	<.001
		Vertical	Parallel	Isochromatic	−0.11	−11.53	<.001
		Vertical	Parallel	Heterochromatic	−0.08	−9.32	<.001
		Vertical	Orthogonal	Isochromatic	−0.11	−15.42	<.001
		Vertical	Orthogonal	Heterochromatic	−0.07	−11.08	<.001
By condition	1				−717	−3.59	<.001
Lag	2	Horizontal	Collinear	Isochromatic	−776	−3.79	<.001
		Horizontal	Collinear	Heterochromatic	−512	−2.49	0.006
		Horizontal	Parallel	Isochromatic	−701	−3.26	0.001
		Horizontal	Parallel	Heterochromatic	−738	−3.75	<.001
		Horizontal	Orthogonal	Isochromatic	−737	−3.33	<.001
		Horizontal	Orthogonal	Heterochromatic	−623	−3.23	0.001
		Vertical	Collinear	Isochromatic	−598	−2.81	0.002
		Vertical	Collinear	Heterochromatic	−523	−2.95	0.002
		Vertical	Parallel	Isochromatic	−616	−3.15	0.001
		Vertical	Parallel	Heterochromatic	−586	−2.84	0.002
		Vertical	Orthogonal	Isochromatic	−790	−3.95	<.001
		Vertical	Orthogonal	Heterochromatic	−595	−3.41	<.001

Appendix B

Minimal errors or lags from Experiment 2 and their permutation distributions were averaged across conditions (in the by-participant test) or participants (in the by-condition test). The differences between the means of the data and the means of the averaged permutation distributions are listed in the 'data mean–permutation mean' column. The corresponding *z*-scores and *p*-values of these differences are listed in the right 2 columns.

Method	Participant	Data mean–permutation mean (dpc)	*z*	*p*
By participant	SYL	−0.12	−17.37	<.001
Minimal error	WYC	−0.11	−17.44	<.001
	LH	−0.10	−16.36	<.001
	CJH	−0.06	−10.62	<.001
	FJ	−0.09	−11.30	<.001
	SM	−0.05	−7.71	<.001
	VX	−0.05	−8.50	<.001
	JS	−0.04	−7.40	<.001
By participant	SYL	−701	−5.04	<.001
Lag	WYC	−572	−4.06	<.001
	LH	−720	−5.18	<.001
	CJH	−654	−6.14	<.001
	FJ	−645	−4.79	<.001
	SM	−585	−4.78	<.001
	VX	−469	−3.35	<.001
	JS	−343	−2.54	0.005

Method	Arrangement	Relative orientation	Relative color	Data mean–permutation mean (dpc)	*z*	*p*
By condition	Horizontal	Collinear	T^-D^-	−0.09	−9.30	<.001
Minimal error	Horizontal	Collinear	T^+D^-	−0.08	−7.61	<.001
	Horizontal	Collinear	T^-D^+	−0.06	−6.09	<.001

(*continued on next page*)

Appendix B (*continued*)

Method	Arrangement	Relative orientation	Relative color	Data mean–permutation mean (dpc)	*z*	*p*
	Horizontal	Orthogonal	T^-D^-	−0.09	−12.29	<.001
	Horizontal	Orthogonal	T^+D^-	−0.08	−10.82	<.001
	Horizontal	Orthogonal	T^-D^+	−0.08	−10.93	<.001
	Horizontal	Parellel	T^-D^-	−0.07	−6.51	<.001
	Horizontal	Parellel	T^+D^-	−0.08	−8.24	<.001
	Horizontal	Parellel	T^-D^+	−0.09	−8.92	<.001
	Vertical	Collinear	T^-D^-	−0.08	−7.75	<.001
	Vertical	Collinear	T^+D^-	−0.11	−9.82	<.001
	Vertical	Collinear	T^-D^+	−0.09	−8.42	<.001
	Vertical	Orthogonal	T^-D^-	−0.06	−8.07	<.001
	Vertical	Orthogonal	T^+D^-	−0.06	−8.39	<.001
	Vertical	Orthogonal	T^-D^+	−0.07	−9.73	<.001
	Vertical	Parallel	T^-D^-	−0.08	−7.76	<.001
	Vertical	Parallel	T^+D^-	−0.07	−6.09	<.001
	Vertical	Parallel	T^-D^+	−0.03	−3.27	0.001
By condition	Horizontal	Collinear	T^-D^-	−595	−3.06	0.001
Lag	Horizontal	Collinear	T^+D^-	−689	−3.31	<.001
	Horizontal	Collinear	T^-D^+	−585	−2.60	0.005
	Horizontal	Orthogonal	T^-D^-	−672	−3.26	0.001
	Horizontal	Orthogonal	T^+D^-	−476	−2.47	0.007
	Horizontal	Orthogonal	T^-D^+	−722	−3.64	<.001
	Horizontal	Parellel	T^-D^-	−542	−2.70	0.003
	Horizontal	Parellel	T^+D^-	−516	−2.68	0.004
	Horizontal	Parellel	T^-D^+	−322	−1.81	0.035
	Vertical	Collinear	T^-D^-	−478	−2.52	0.006
	Vertical	Collinear	T^+D^-	−608	−3.14	0.001
	Vertical	Collinear	T^-D^+	−728	−3.61	<.001
	Vertical	Orthogonal	T^-D^-	−557	−2.74	0.003
	Vertical	Orthogonal	T^+D^-	−731	−3.64	<.001
	Vertical	Orthogonal	T^-D^+	−634	−3.14	0.001
	Vertical	Parallel	T^-D^-	−625	−3.09	0.001
	Vertical	Parallel	T^+D^-	−524	−2.74	0.003
	Vertical	Parallel	T^-D^+	−548	−2.95	0.002

Appendix C

Minimal errors or lags from Experiment 3 and their permutation distributions were averaged across conditions (in the by-participant test) or participants (in the by-condition test). The differences between the means of the data and the means of the averaged permutation distributions are listed in the 'data mean–permutation mean' column. The corresponding *z*-scores and *p*-values of these differences are listed in the right 2 columns.

Method	Participant	Data mean–permutation mean (dpc)	*z*	*p*
By participant	AOH	−0.08	−9.69	<.001
Minimal error	EK	−0.01	−1.32	0.093
	FJ	−0.12	−10.99	<.001
	KC	−0.12	−14.46	<.001
	SM	−0.05	−7.24	<.001
	SYL	−0.16	−17.05	<.001
	VX	−0.06	−8.36	<.001
	WYC	−0.12	−15.40	<.001
By participant	AOH	−368	−2.64	0.004
Lag	EK	4	0.02	0.510
	FJ	−765	−4.54	<.001
	KC	−769	−4.78	<.001
	SM	−524	−3.04	0.001
	SYL	−698	−4.47	<.001
	VX	−398	−2.35	0.009
	WYC	−632	−3.71	<.001

Appendix C (*continued*)

Method	Relative orientation	Relative color	Data mean–permutation mean (dpc)	z	p
By condition	Collinear	T^+D^-	−0.12	−10.03	<.001
Minimal error	Collinear	T^+D^+	−0.10	−8.09	<.001
	Collinear	$T^-D_{feature}$	−0.10	−8.03	<.001
	Collinear	$T^-D_{location}$	−0.10	−8.66	<.001
	Orthogonal	T^+D^-	−0.10	−10.62	<.001
	Orthogonal	T^+D^+	−0.11	−12.15	<.001
	Orthogonal	$T^-D_{feature}$	−0.10	−11.40	<.001
	Orthogonal	$T^-D_{location}$	−0.11	−12.95	<.001
	Parallel	T^+D^-	−0.09	−7.85	<.001
	Parallel	T^+D^+	−0.10	−8.87	<.001
	Parallel	$T^-D_{feature}$	−0.09	−6.96	<.001
	Parallel	$T^-D_{location}$	−0.09	−7.37	<.001
By condition	Collinear	T^+D^-	−527	−2.79	0.003
Lag	Collinear	T^+D^+	−629	−3.06	0.001
	Collinear	$T^-D_{feature}$	−507	−2.19	0.014
	Collinear	$T^-D_{location}$	−619	−2.69	0.004
	Orthogonal	T^+D^-	−636	−3.00	0.001
	Orthogonal	T^+D^+	−584	−2.58	0.005
	Orthogonal	$T^-D_{feature}$	−559	−2.70	0.003
	Orthogonal	$T^-D_{location}$	−705	−3.46	<.001
	Parallel	T^+D^-	−373	−1.93	0.027
	Parallel	T^+D^+	−581	−2.58	0.005
	Parallel	$T^-D_{feature}$	−687	−3.24	0.001
	Parallel	$T^-D_{location}$	−715	−3.18	0.001

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